Effects of MHD on fast ion confinement in SPARC

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Outline

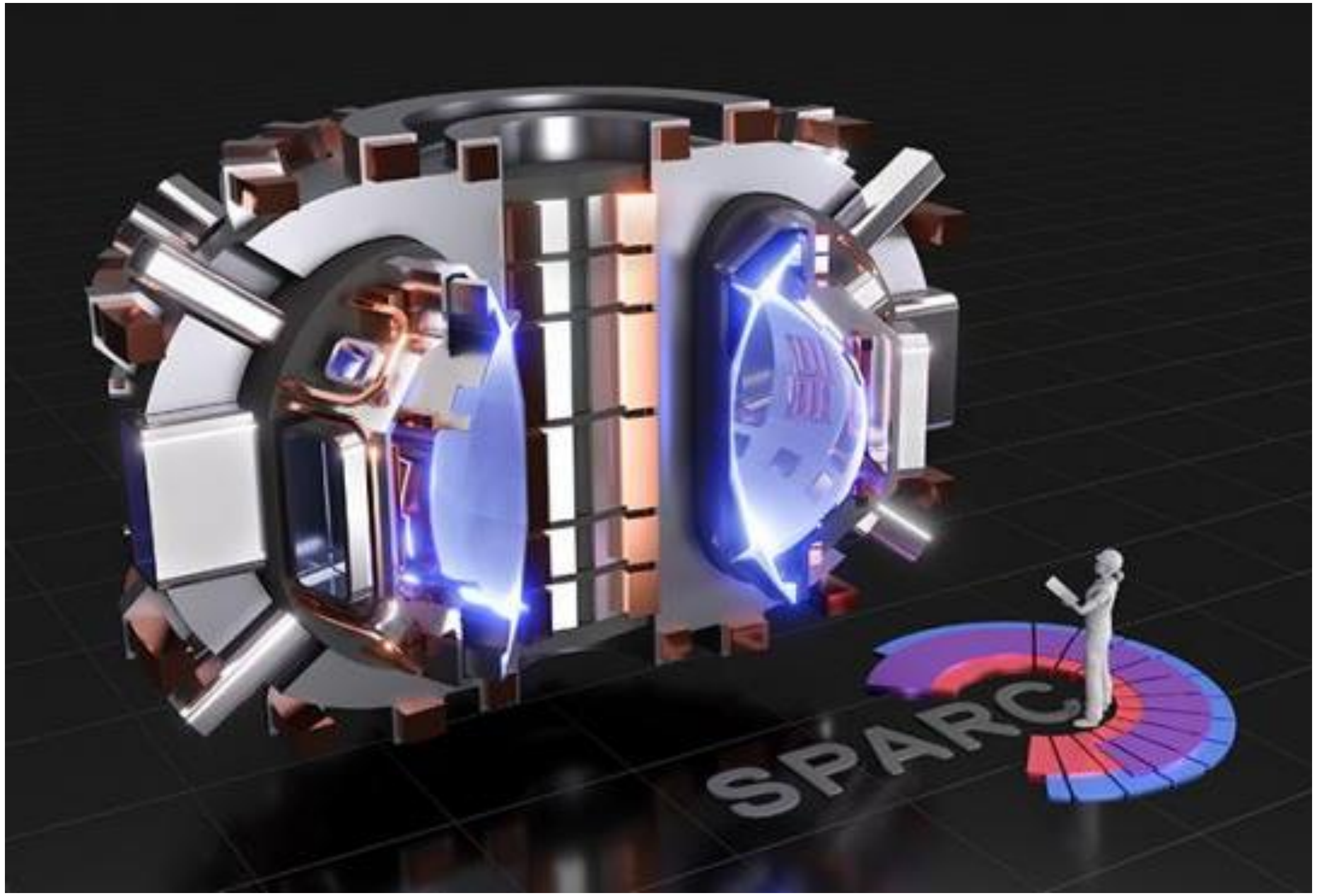
- Introducing SPARC
- Low frequency MHD, NTMs + TF ripple
- High frequency MHD, Alfven Eigenmodes
- Diagnostics, opportunities and challenges
- Summary and future work

Introducing SPARC

SPARC is a high-field, compact, DT tokamak under construction in Devens, MA; first plasma 2025

full-field DT H-mode	
R_0	1.85 m
a	0.57 m
B_T	12.2 T
I_P	8.7 MA
q_{95}	3.4
κ_{95}	1.75
f_G	0.37
β_N	1.0
P_{ICRH}	11.1 MW
P_{fusion}	140 MW
Q	11

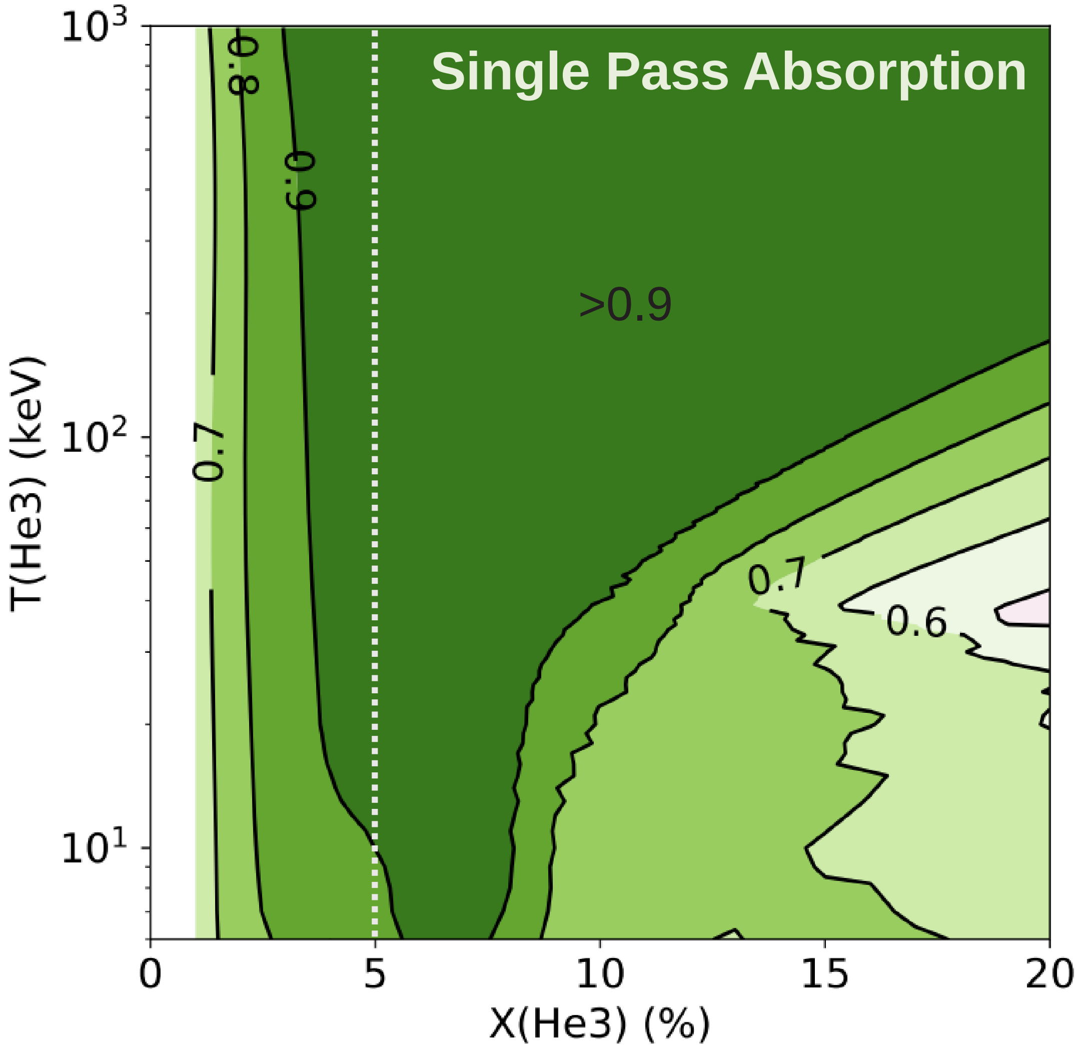
[Creely 2020 JPP]



https://www.psfc.mit.edu/sparc

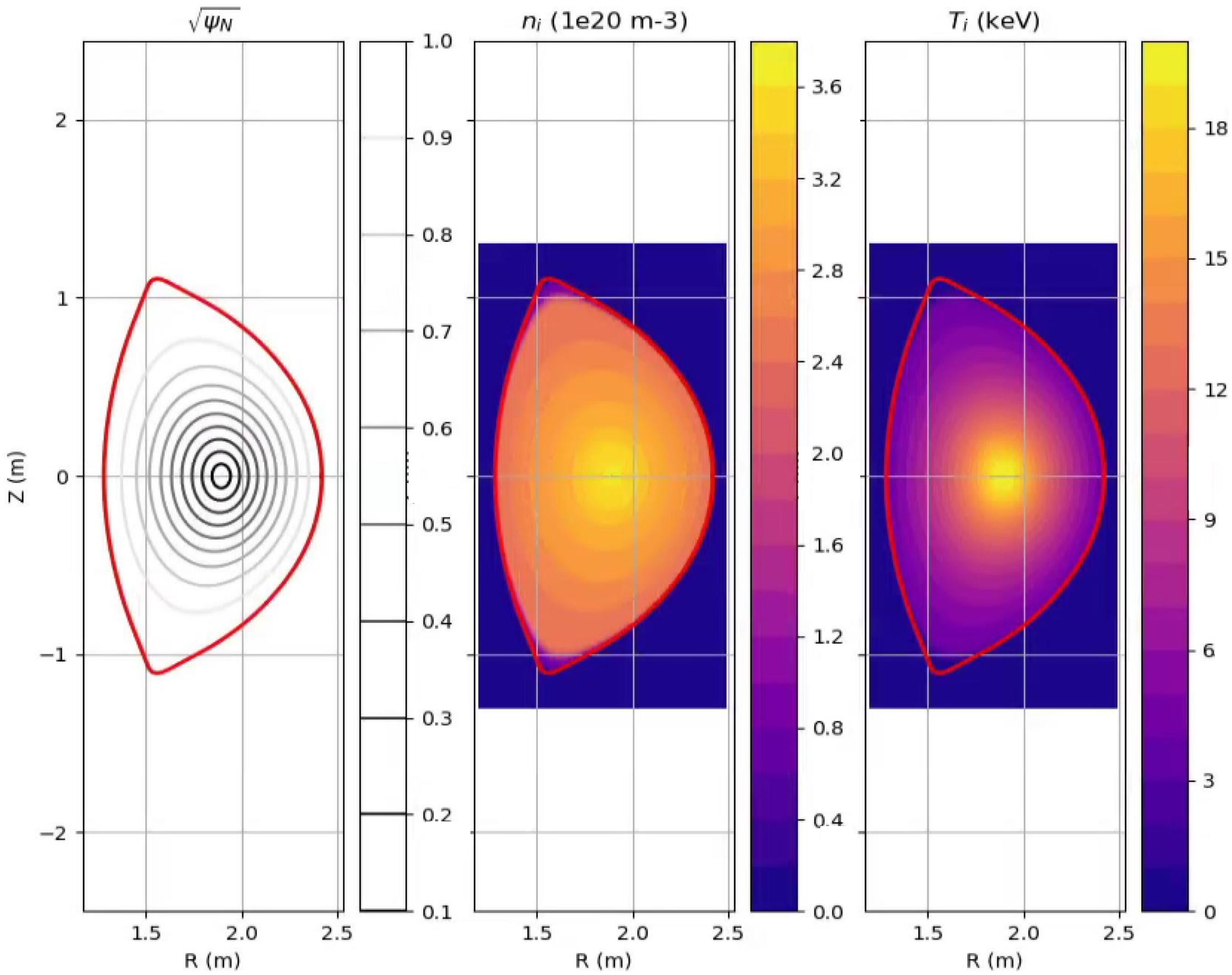
SPARC will use only Ion Cyclotron Resonance Heating

- No Neutral Beam Injection
- f = 120 MHz at B_0 = 12 T
  - Fundamental He3
  - Second harmonic T
- P_{ICRH} ~ 25-30 MW



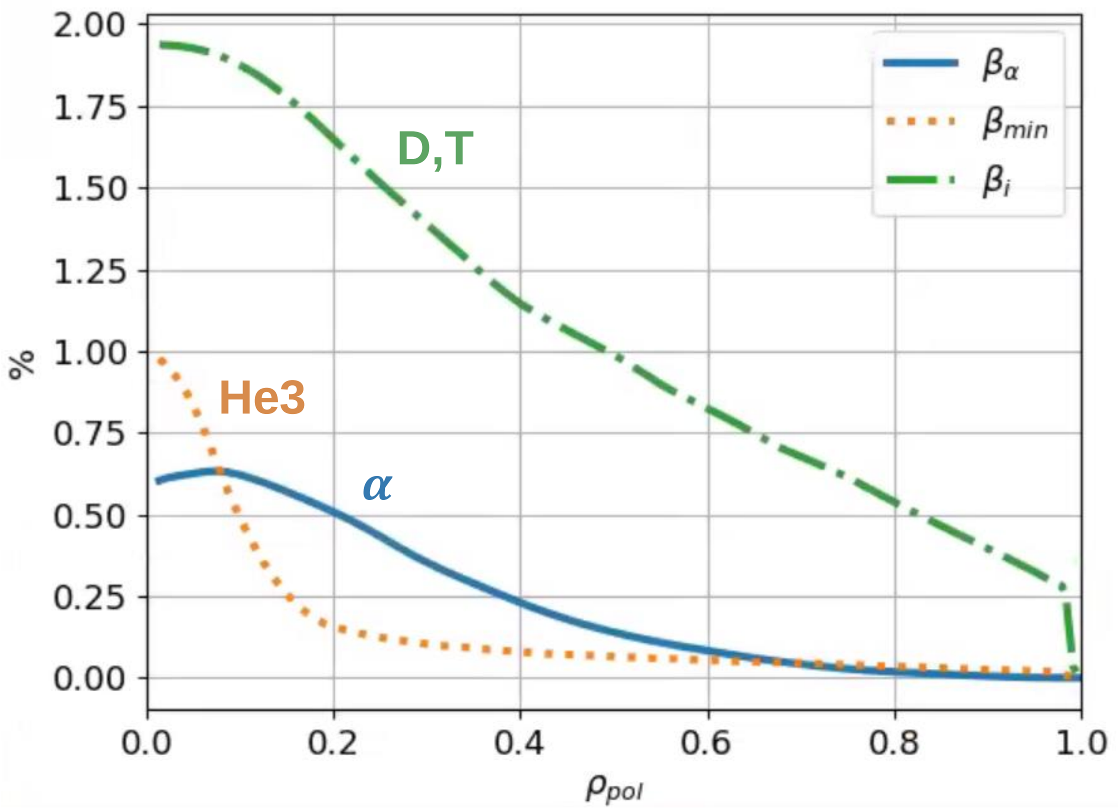
[Lin 2020 JPP]

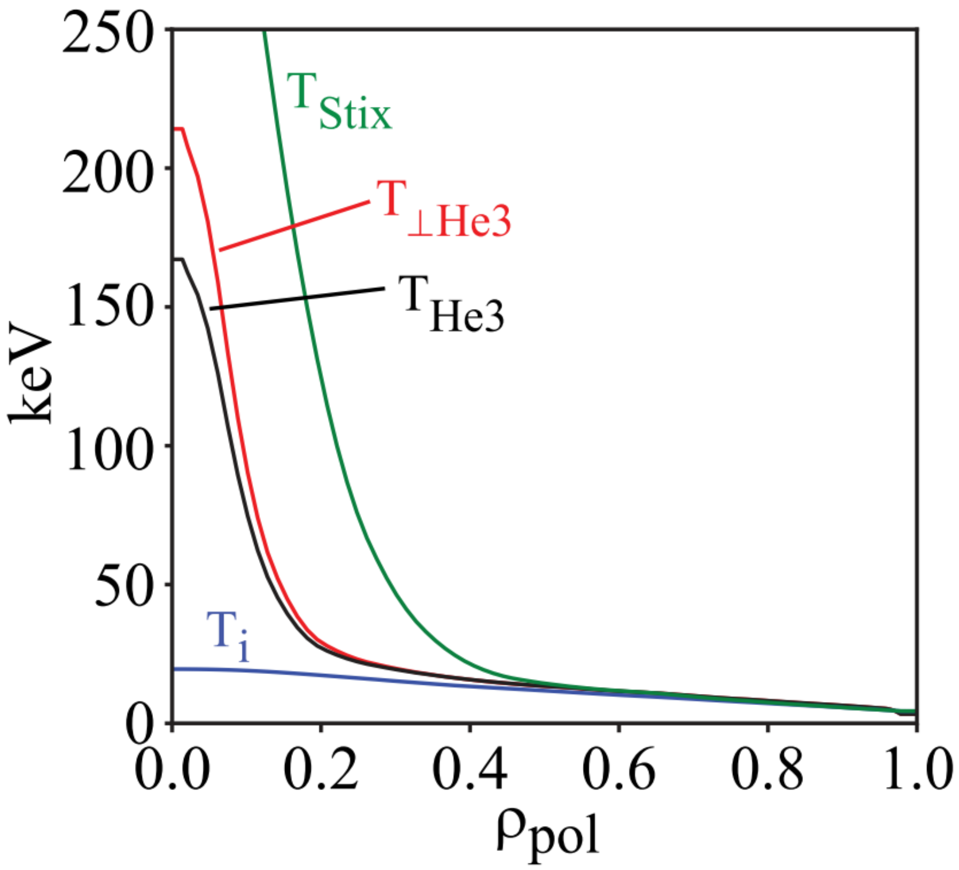
SPARC's Primary Reference Discharge (PRD) has peak density ~4e20 m^{-3} and temperature ~20 keV



[Creely 2020 JPP, Rodriguez Fernandez 2020 JPP]

Fast ion (He3 minority) population is more peaked than alpha population in SPARC





[Scott 2020 JPP]

SPARC and ITER have similar alpha parameters

- Alfven speed $v_A = 9 \times 10^6$ m/s
- Thermal D speed $v_D = 1 \times 10^6$ m/s
- Alpha speed $v_\alpha = 13 \times 10^6$ m/s

- Alpha Larmor radius $\rho_\alpha \sim 2$ cm
- Alpha banana orbit width $\delta_\alpha < 12$ cm

- Alpha beta $\beta_\alpha \sim 0.6\%$
- Thermal beta $\beta_{th} \sim 4\%$

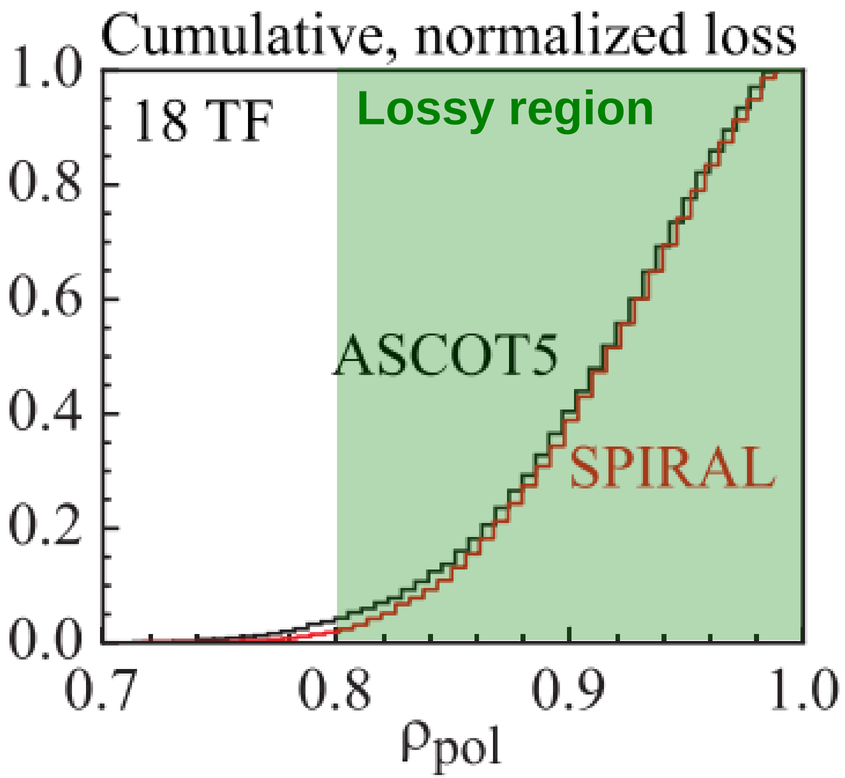
- Unstable toroidal modes $n = 13 - 20$
- High-B [Tolman 2019 NF] → $n = 30 - 40$

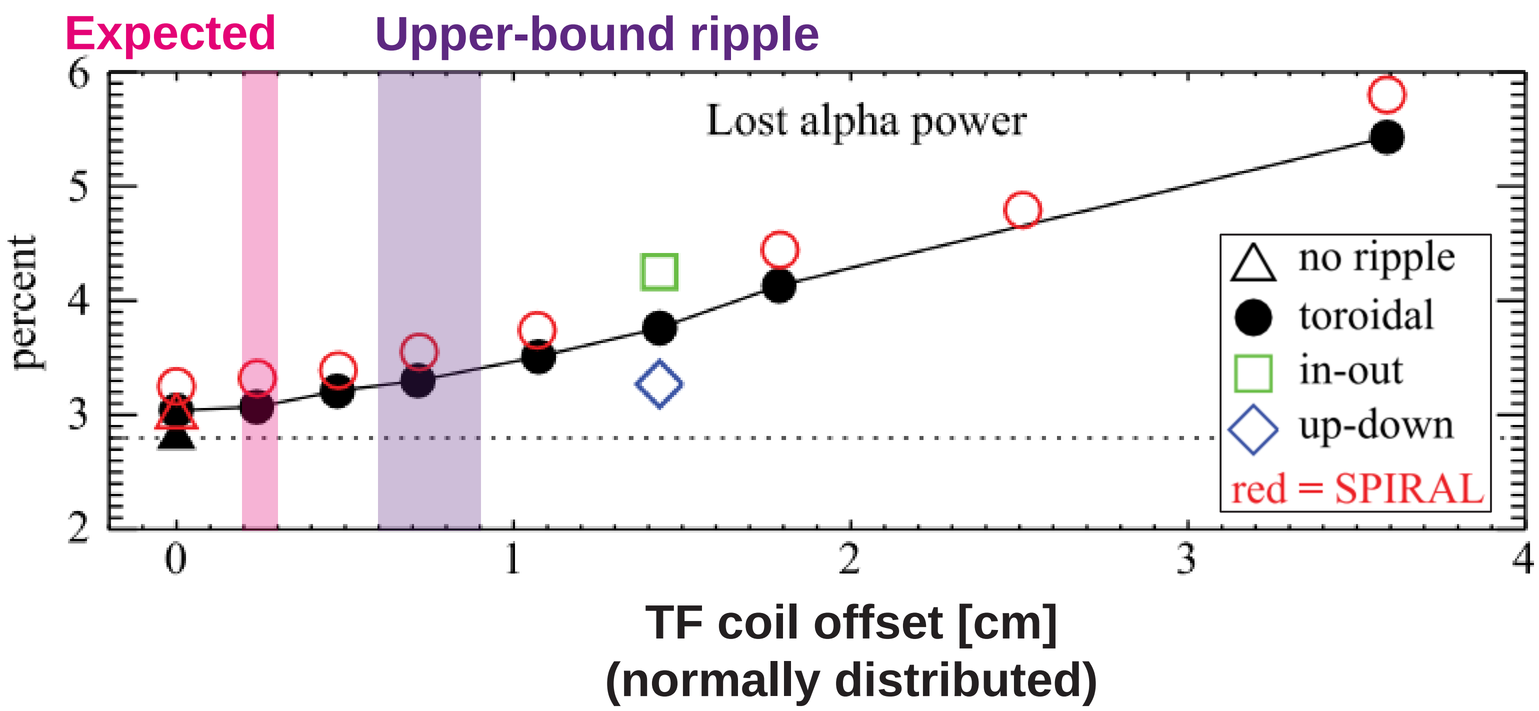
	ITER/SPARC	
	$Q = 3$	$Q = 9$
β_α / β	2.46	1.23
V_A	0.94	0.97
$n_{\max}$	1.64	1.58

[Scott 2020 JPP]

Low frequency MHD, NTMs + TF ripple

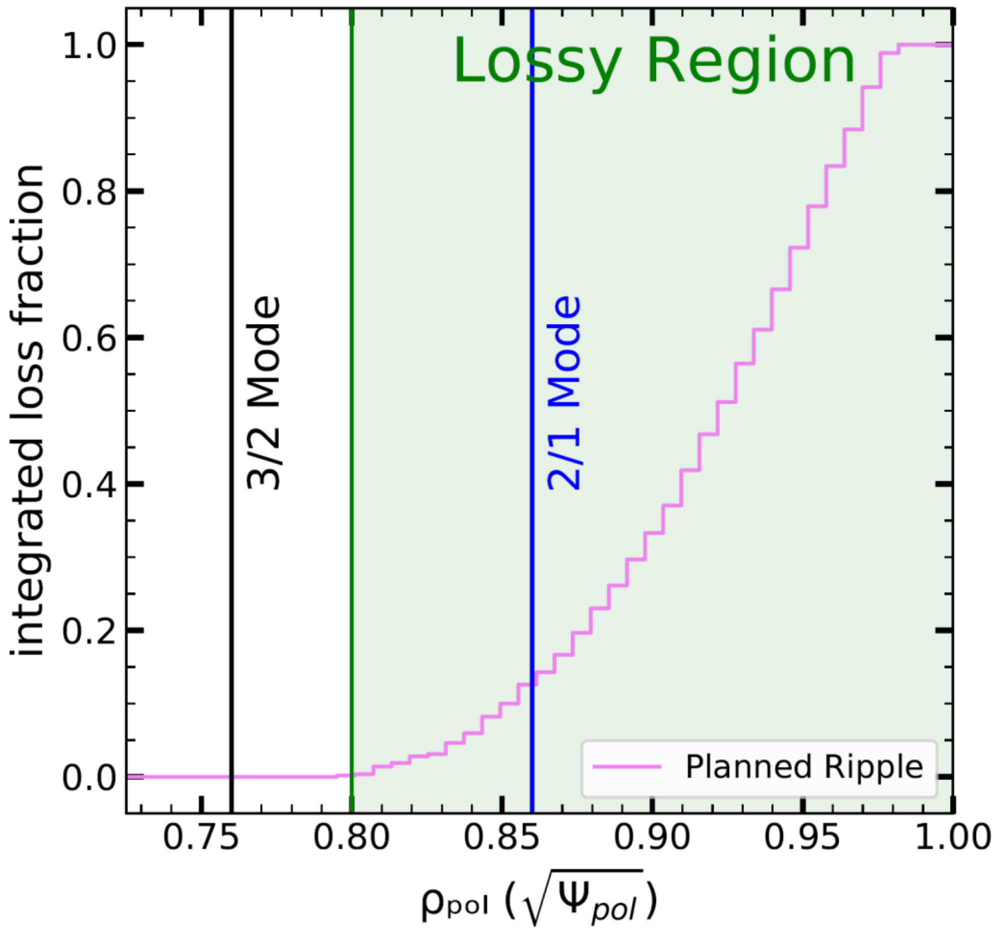
Toroidal field ripple leads to alpha particle/ power loss ~ 500 kW



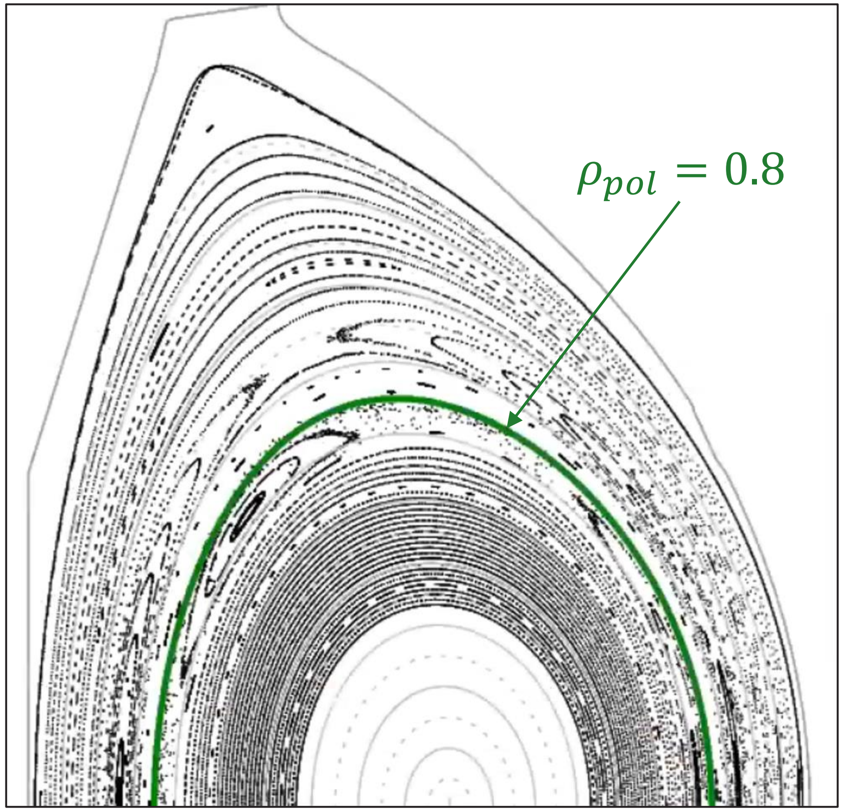


[Scott 2020 JPP]

Neoclassical tearing modes m/n = 3/2 and 2/1 modeled with SPIRAL

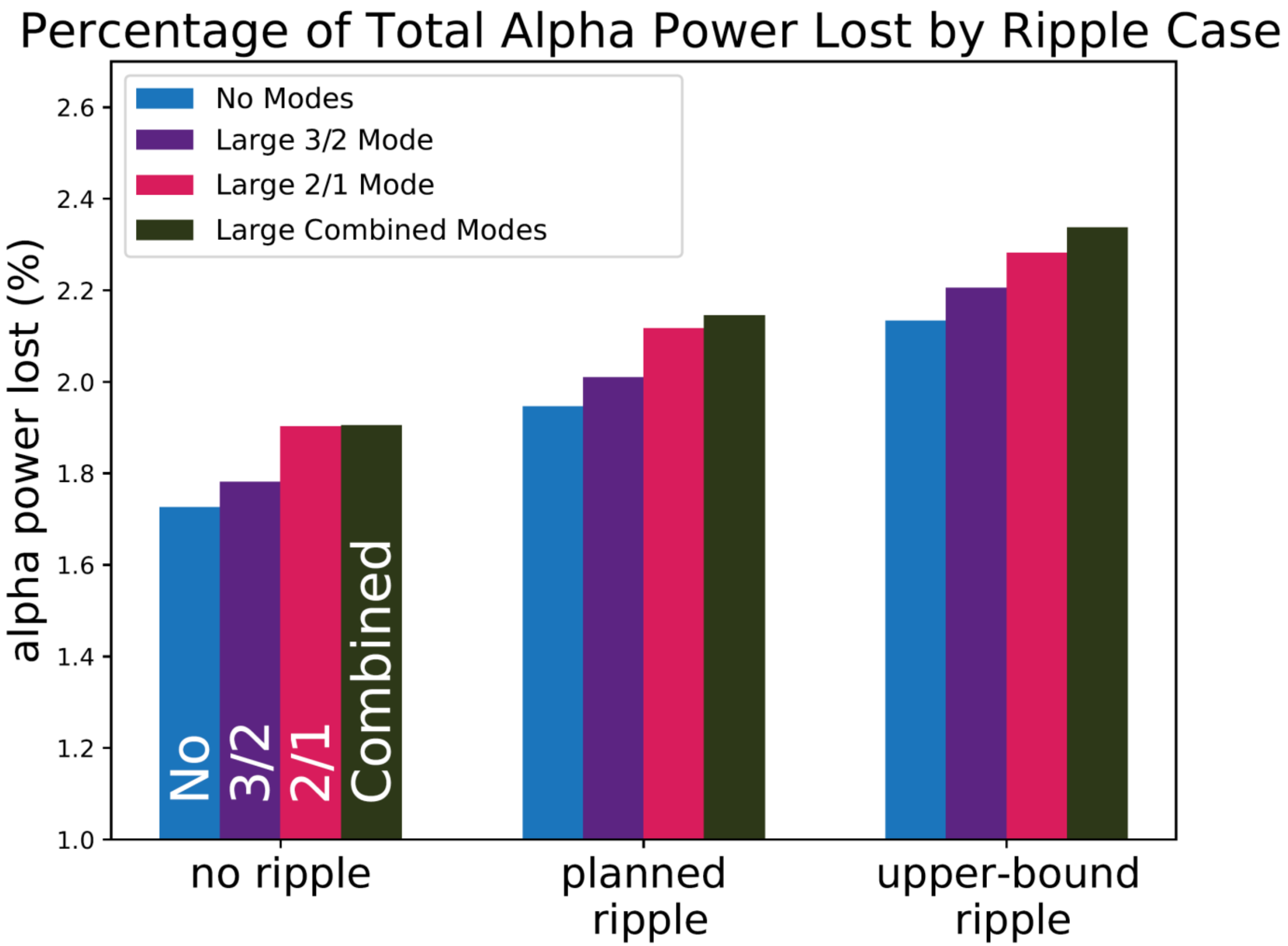


Combined 3/2 + 2/1 NTMs



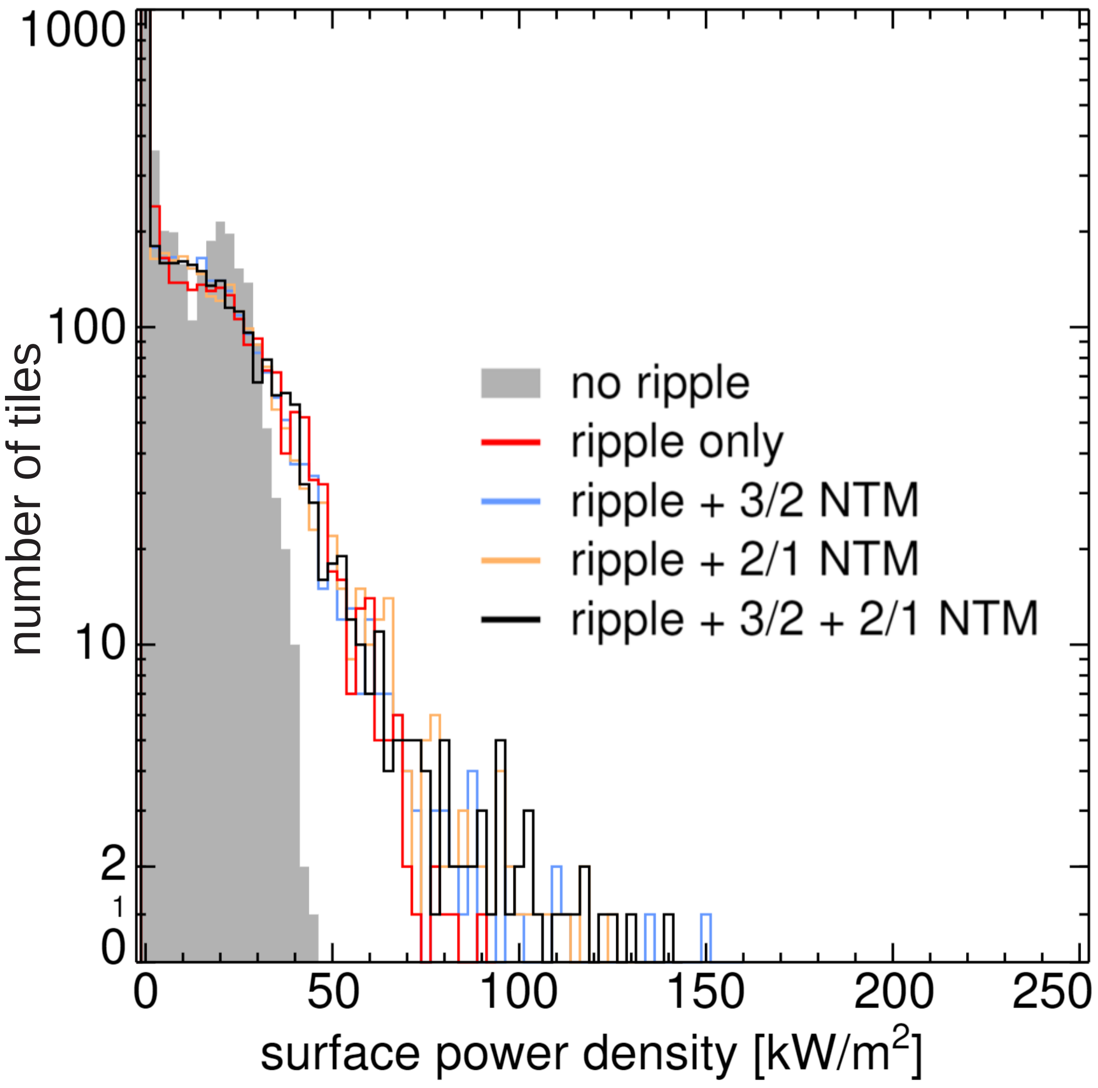
[Kramer 2013 PPCF, Braun 2022 In progress]

Increase in alpha power loss is modest ~2% → ~2.2%, but total power loss remains low <700 kW



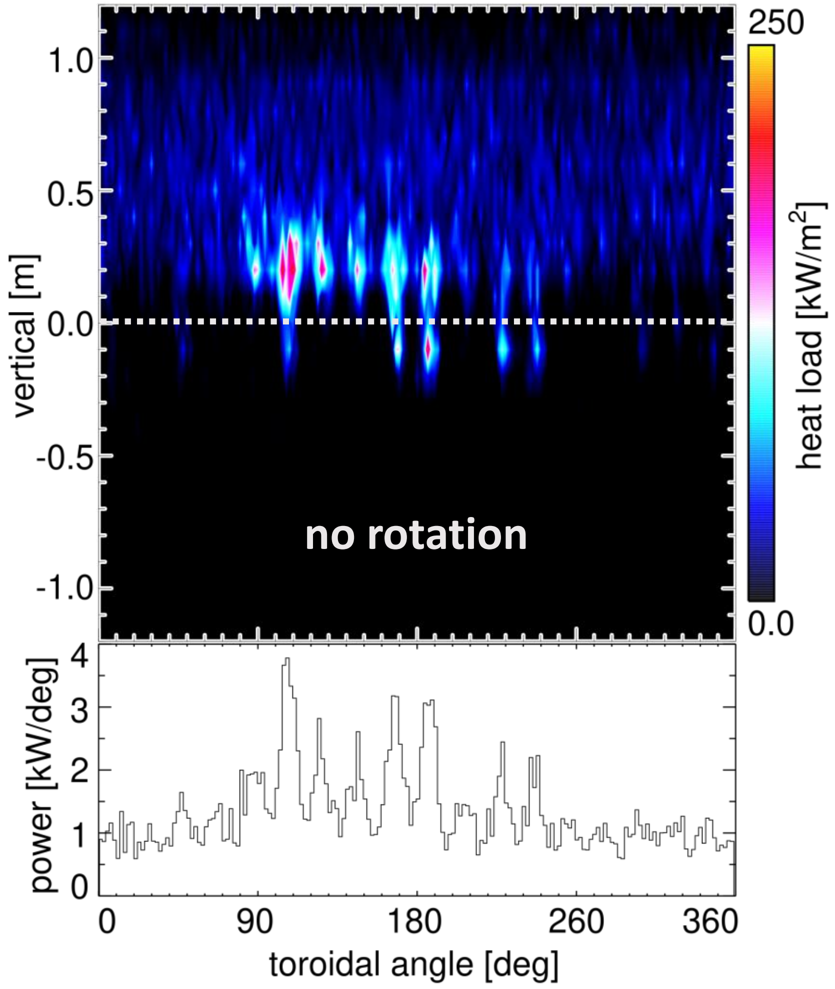
[Braun 2022 In progress]

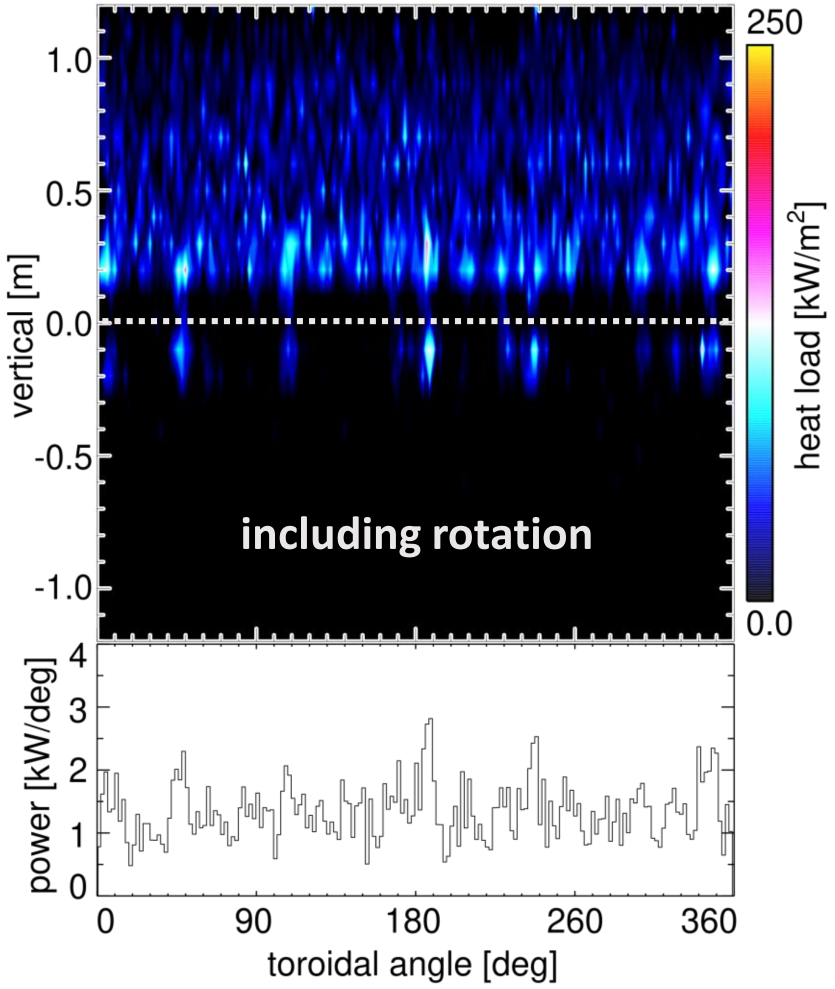
First-wall heat flux from alphas increases by ~50%, ~100 kW/m² → 150 kW/m² (flat wall assumption)



[Braun 2022 In progress]

Heat flux may be concentrated for a locked mode, but spread out with intrinsic rotation <10 kHz



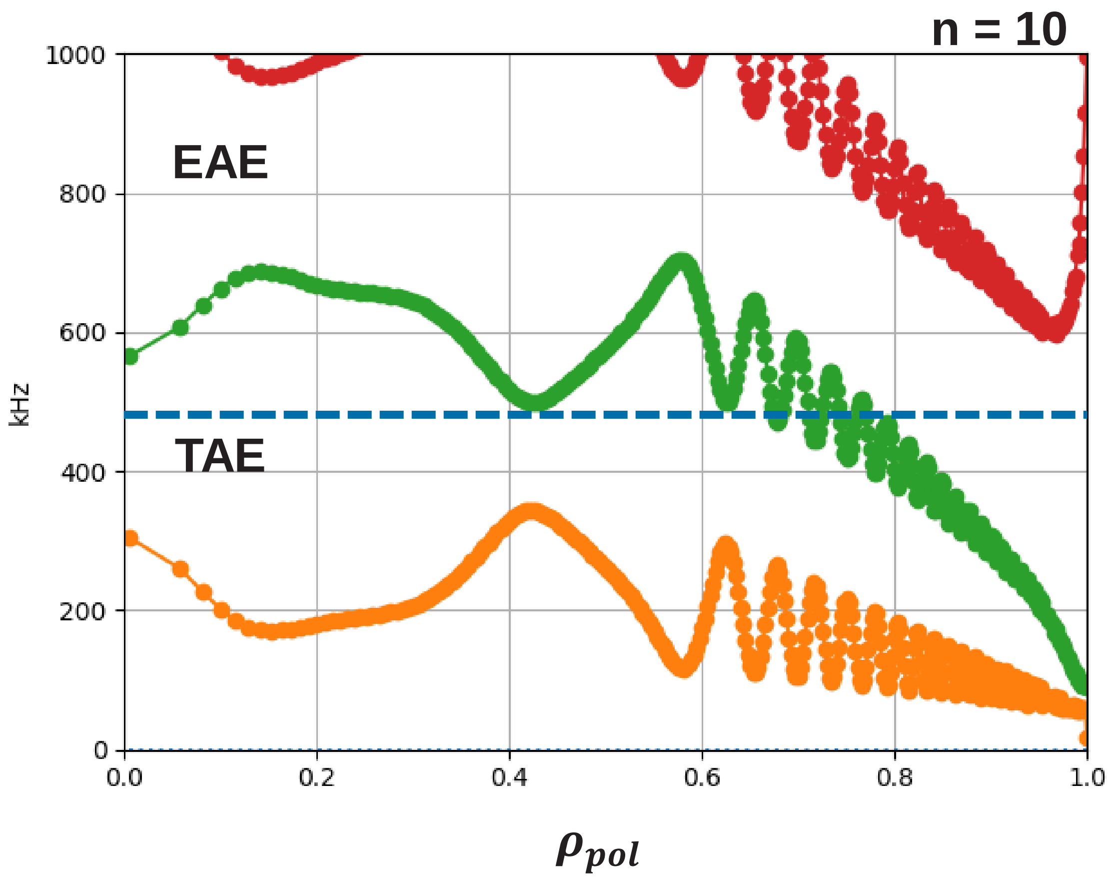


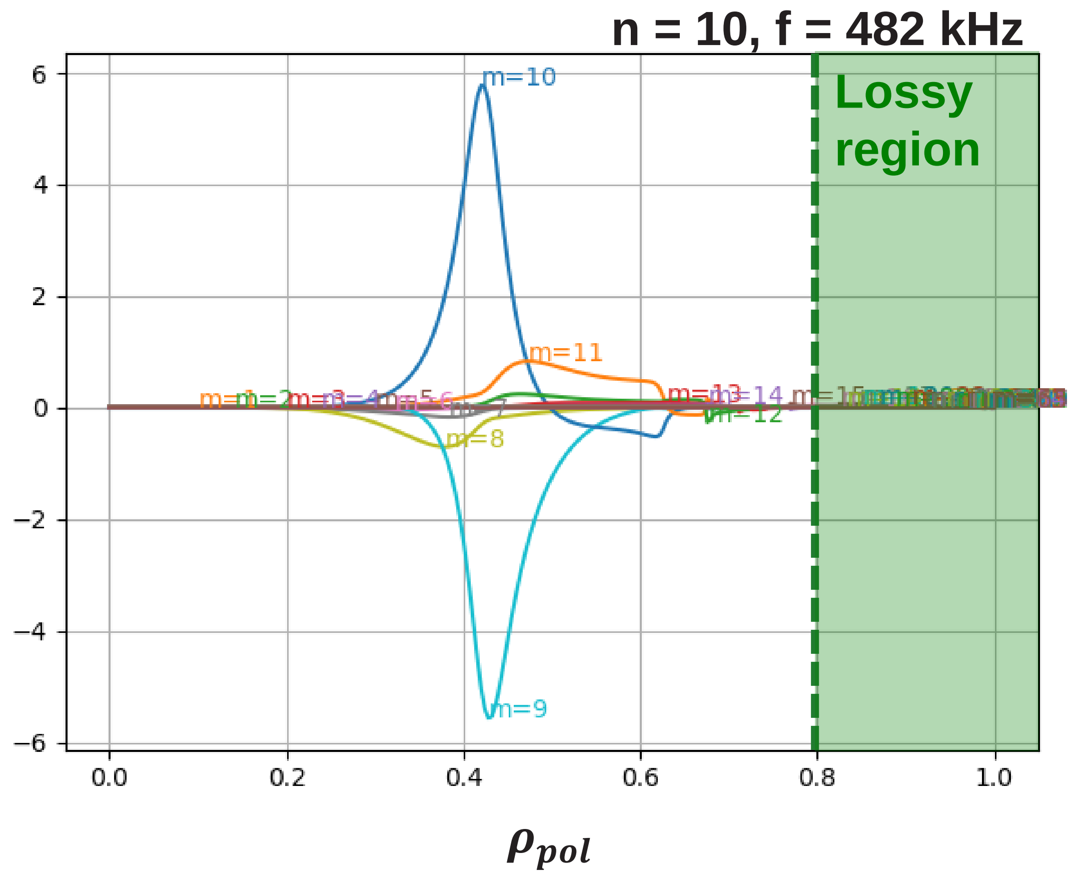
- Upper-bound ripple
- Toroidally symmetric first wall

[Braun 2022 In progress]

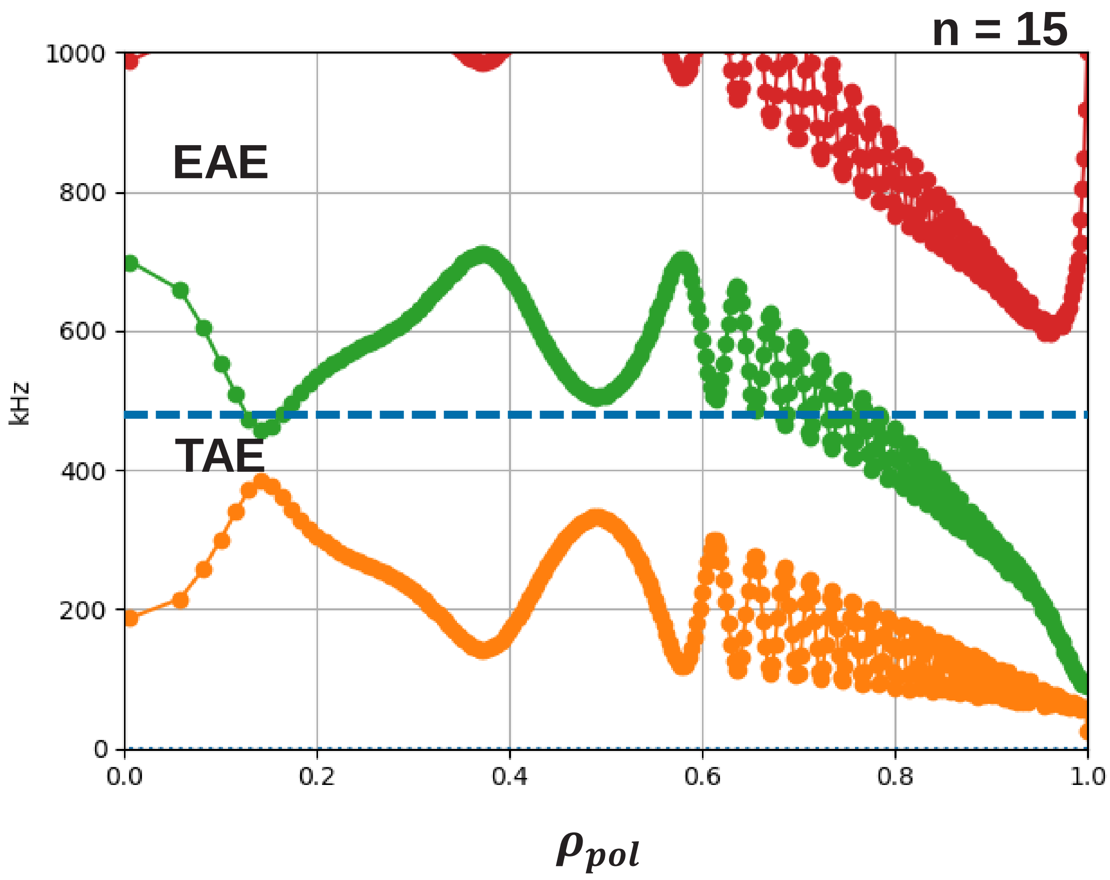
High frequency MHD, Alfven Eigenmodes

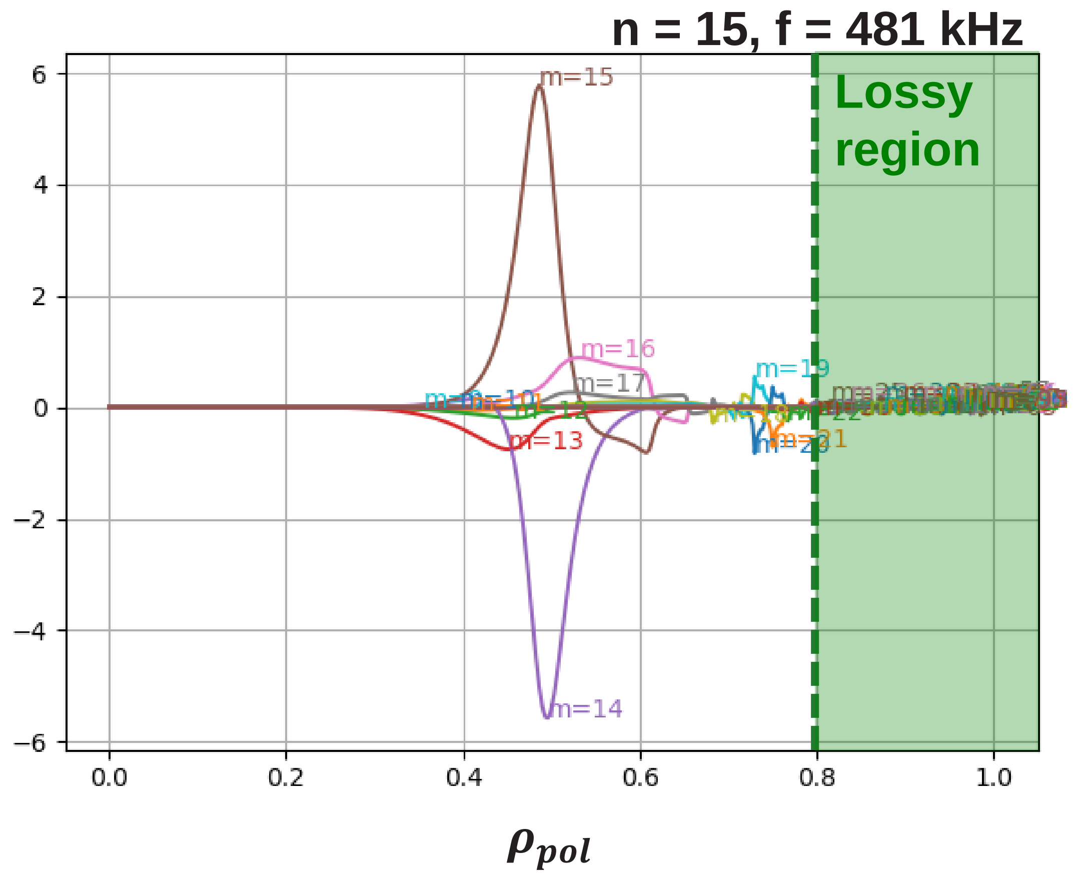
n = 10 Alfven continua and eigenmode structures calculated with NOVA (without rotation)





n = 15 Alfven continua and eigenmode structures calculated with NOVA (without rotation)





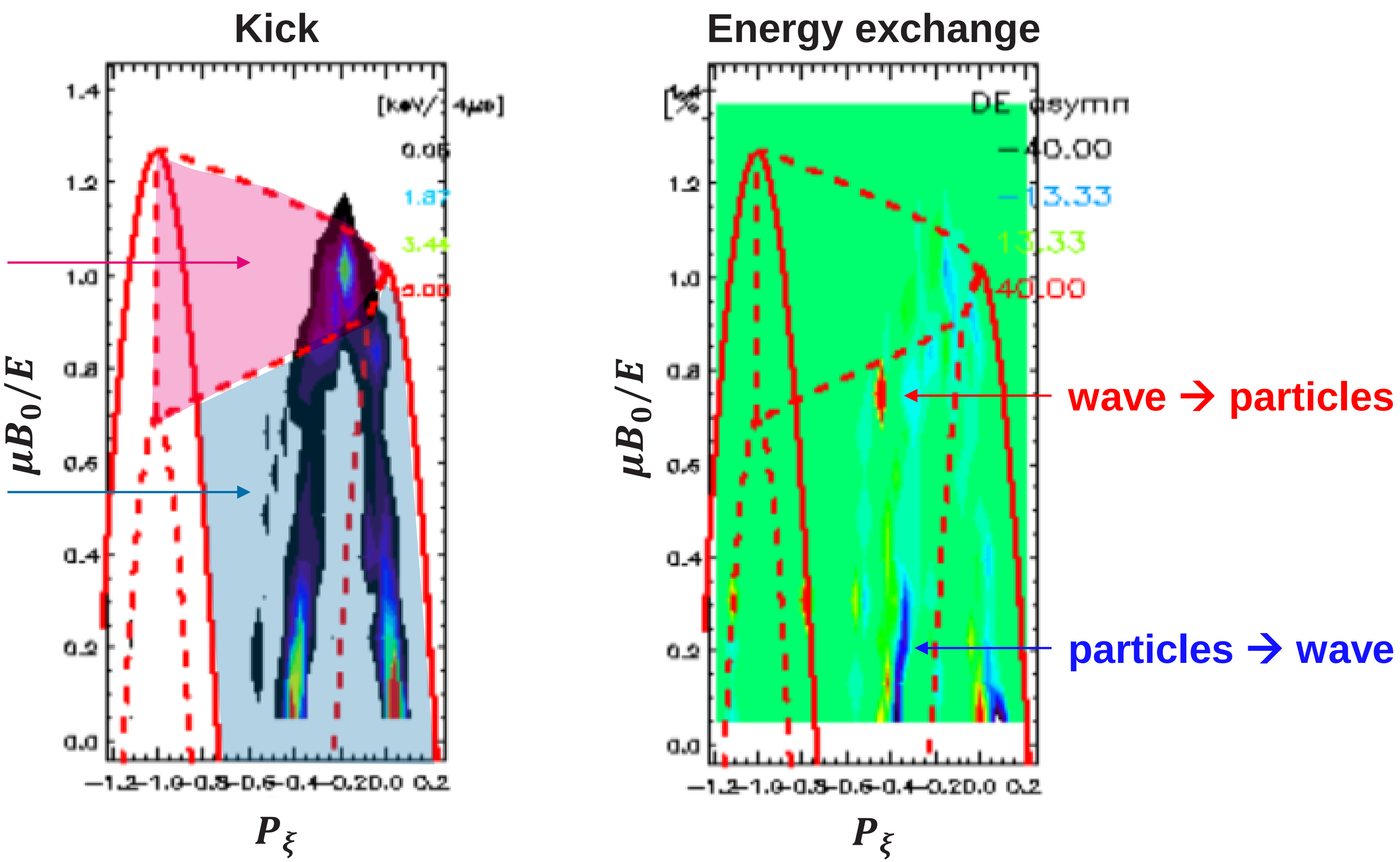
NOVA-K calculates stability breakdown; He3 minority *stabilizes* AEs perhaps due to $v_{He3} \sim v_A$

Drive/Damping γ/ω_0 (%)	n = 5 350 kHz	n = 10 482 kHz	n = 15 481 kHz	n = 20 370 kHz
Continuum	~ 0.0	~ 0.0	~ 0.0	~ 0.0
Radiative	-0.3	~ 0.0	~ 0.0	-2.6
Electron collisional	~ 0.0	~ 0.0	~ 0.0	~ 0.0
Electron Landau	-0.1	~ 0.0	~ 0.0	~ 0.0
Ion Landau	~ 0.0	~ 0.0	~ 0.0	-0.1
He3 minority	-0.1	-0.1	-0.1	-0.4
Alphas	~ 0.0	$+0.3$	$+0.3$	$+0.7$
Intrinsic damping	-0.4	-0.1	-0.1	-2.8
Total growth rate	-0.5	$+0.2$	$+0.1$	-2.4

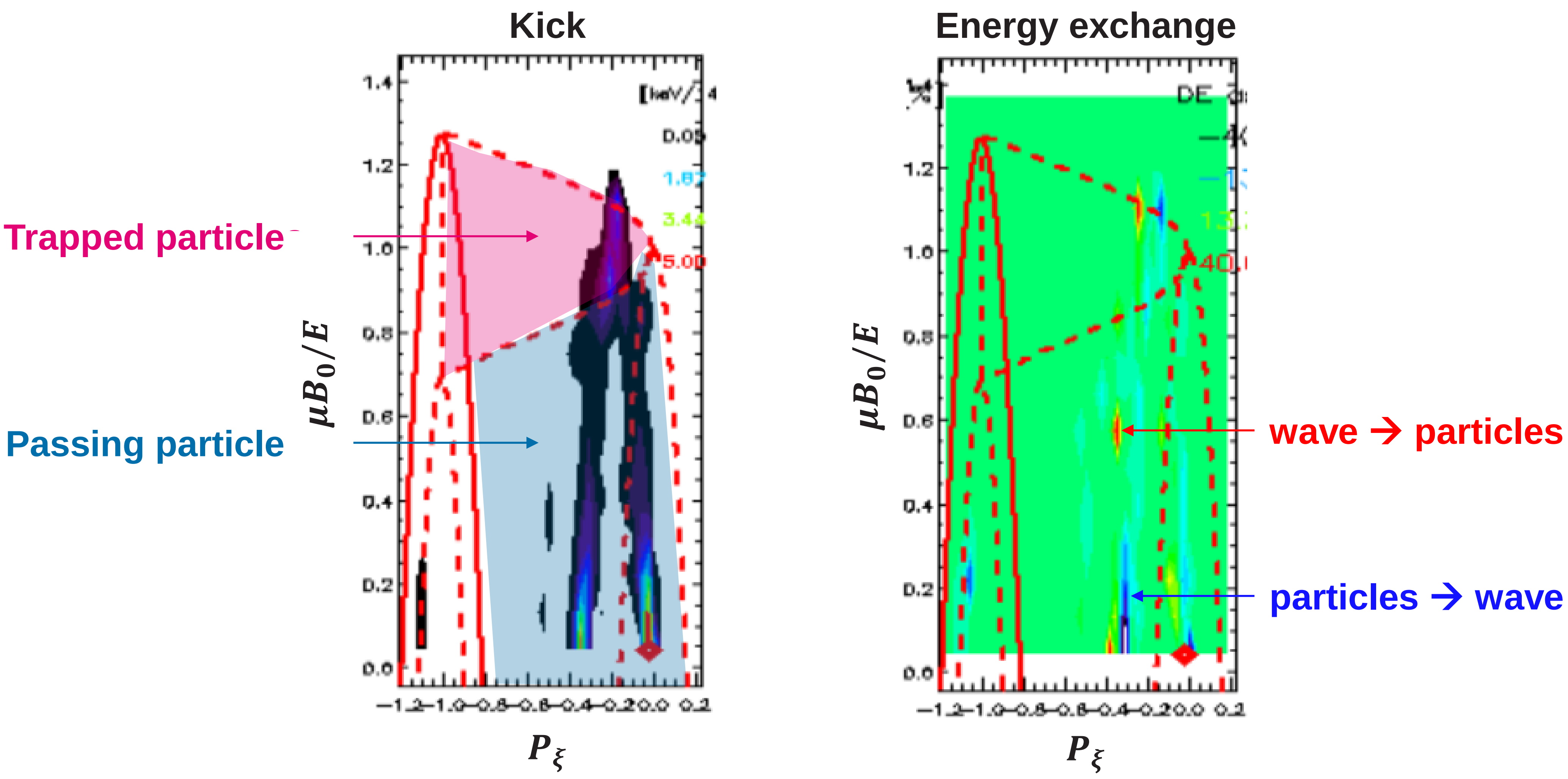
ORBIT calculates wave-particle interactions over *all* of phase-space: n = 10 TAE + 3.5 MeV alphas

Trapped particles

Passing particles



ORBIT calculates wave-particle interactions over *all* of phase-space: n = 10 TAE + 2.4 MeV He3



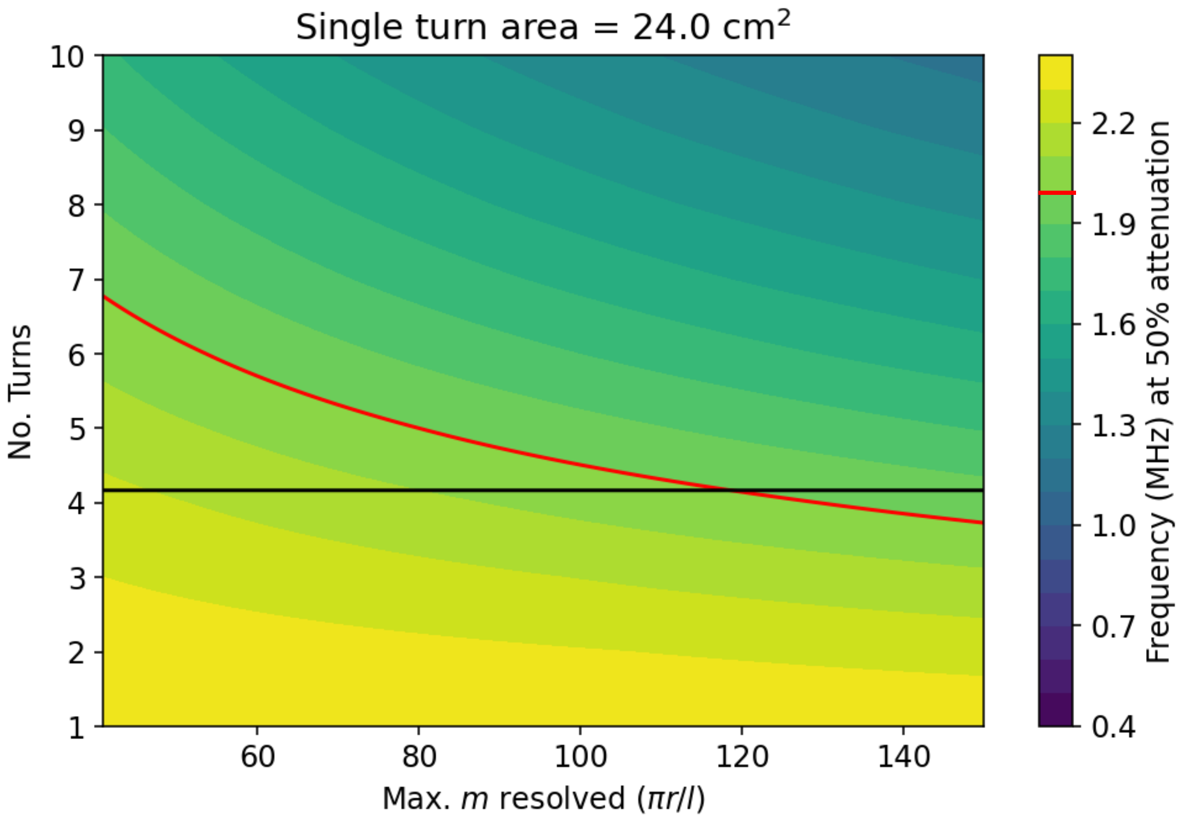
Diagnostics, opportunities and challenges

At least one high-frequency Mirnov array is planned for AE measurements

- $n \leq 40$
- $m \leq 120$ (for $q \leq 3$)

- f_{TAE} = ~500 kHz + 40*10 kHz = 900 kHz
- f_{EAE} = ~1 MHz + 40*10 kHz = 1.4 MHz
- Digitization rate >2 MS/s

- Other diagnostics:
  - Interferometry (density)
  - Soft X-Ray (temperature)

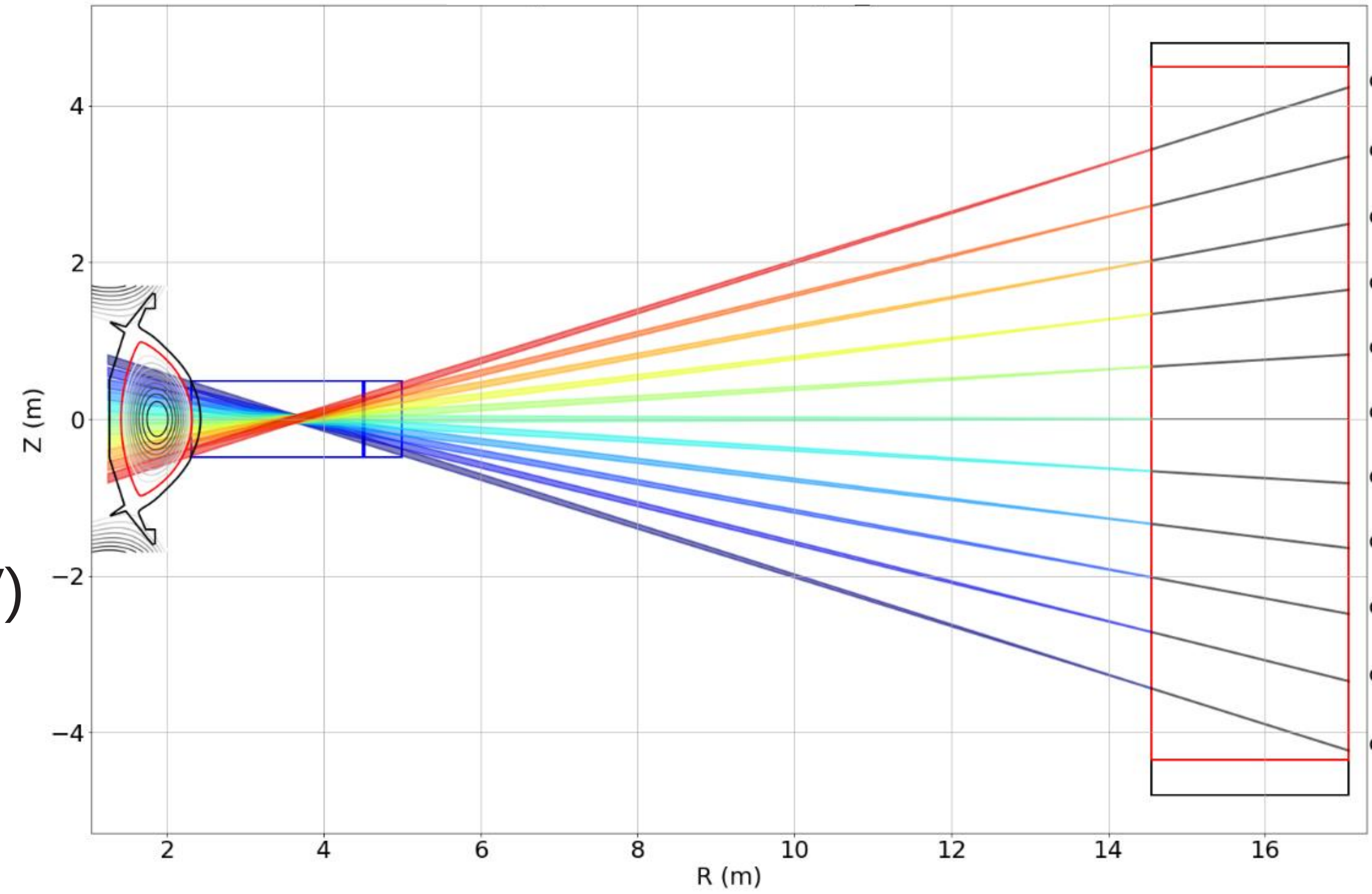


[R Sweeney]

Neutron camera/spectrometer is planned for neutron/alpha birth profile measurements

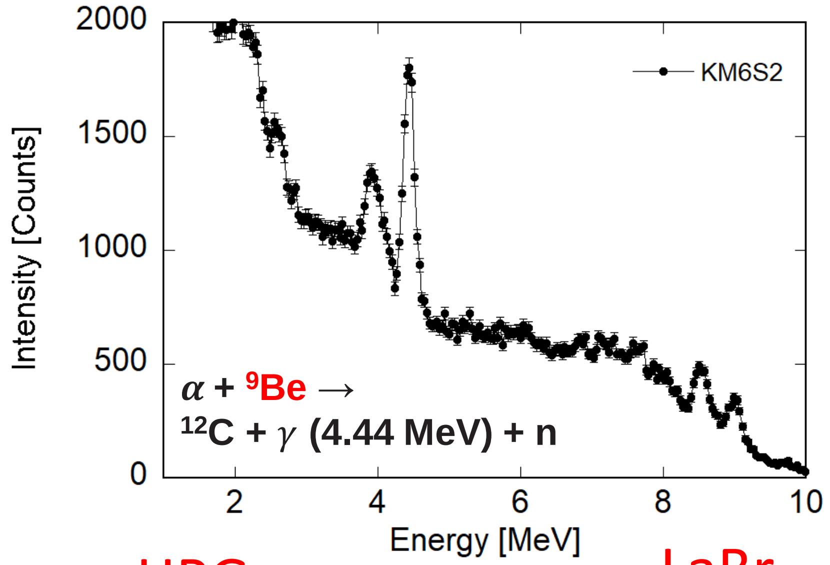
- Neutron flux sufficiently high
→ spectrometers along several lines-of-sight
  - Magnetic Proton Recoil
  - Compact CVD diamond

- High-energy neutron tail (<20 MeV)
  - ICRH tail
  - Alpha knock-on neutrons



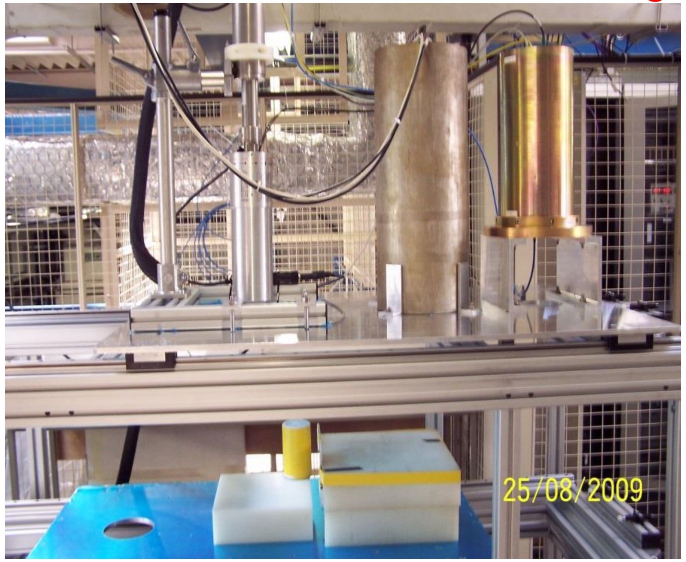
Scoping underway for gamma ray diagnostics

- Look at *confined* alpha population
- Incorporate into neutron camera lines-of-sight?
- Reactions of interest:
  - No Beryllium (unlike JET and ITER)
  - Boronization:
    $^{10}B(\alpha,\gamma)^{13}C$ → ~3.1, 3.7, 3.85 MeV gammas
  - He3 minority heating:
    $\alpha(^{3}He,\gamma)^{7}Be$ → ~3e12 gammas/s in PRD
  - D+T → (1e-5) $^{5}He^{*}$ → $^{5}He + \gamma$ (16.7 MeV)



HPGe

LaBr$_3$



[Tardocchi 2020 Varenna]

Summary and future work

Summary

- SPARC is under construction, with first plasma ~2025 and PRD ~2027
- TF ripple alone could cause alpha power loss <2.2% (<620 kW), and large 3/2 or 2/1 NTMs could increase this to <2.4% (<680 kW)
- n = 10 – 15 TAEs could be (marginally) destabilized by alphas, while He3 is interestingly stabilizing, near q = 1 in the PRD
- Diagnostics for the alpha birth profile and high-frequency fluctuations are being designed

Future work

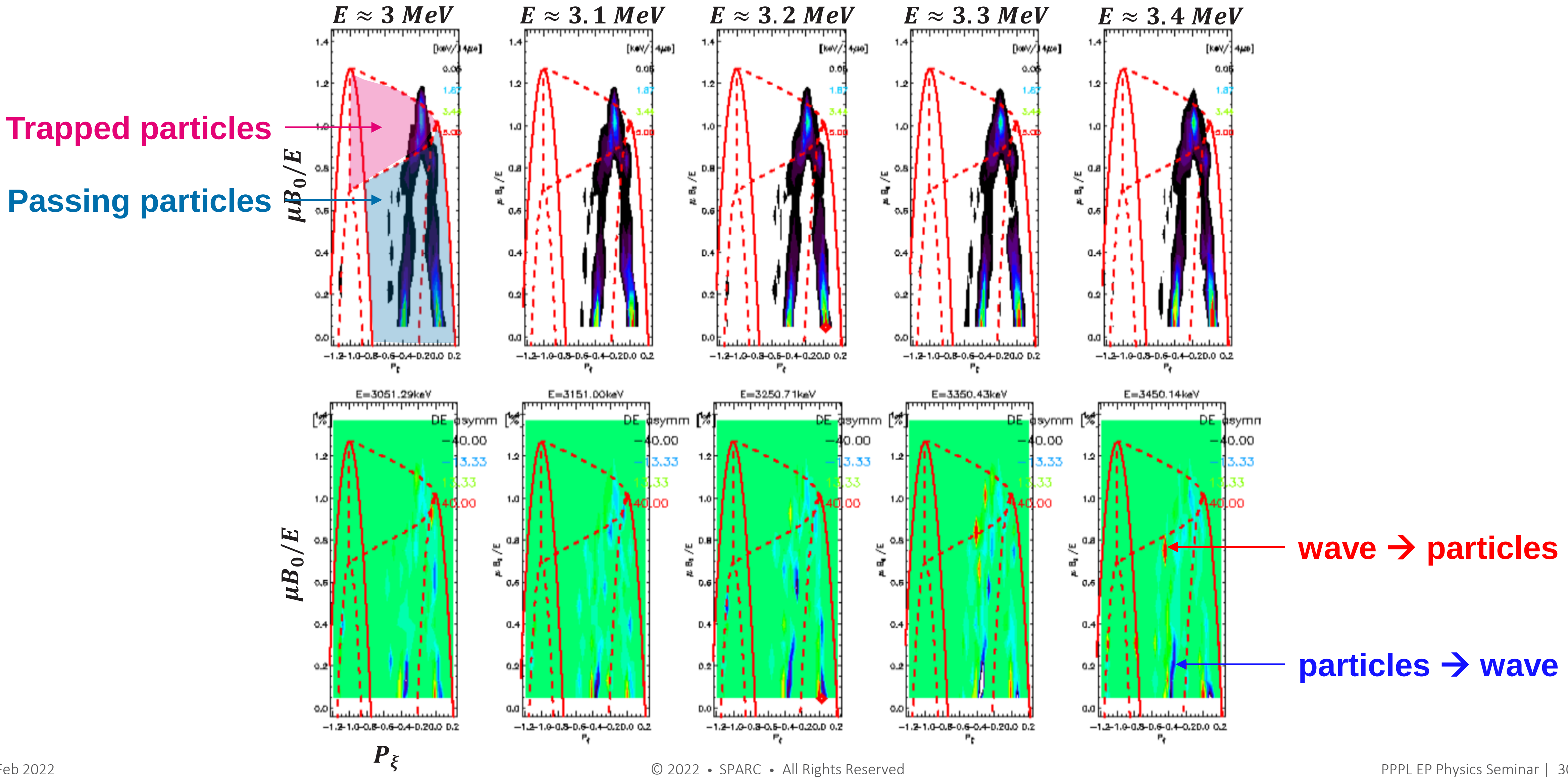
- Evaluate other SPARC scenarios, e.g. Q ~ 1 and 5
- Assess other low-frequency modes, e.g. sawteeth and ELMs
- Perform toroidal mode number scan and more advanced simulations
- Scope diagnostics for confined alpha particles
- Collaborations are very welcome!

Bonus

NOVA-K calculates stability breakdown; He3 minority *stabilizes* AEs perhaps due to $v_{He3} \sim v_A$

Drive/Damping	n = 5		n = 10		n = 15		n = 20	
γ/ω_0 (%)	**292 kHz**	**350 kHz**	**361 kHz**	**482 kHz**	**360 kHz**	**481 kHz**	**341 kHz**	**370 kHz**
Continuum	-0.1	~ 0.0	~ 0.0	~ 0.0	~ 0.0	~ 0.0	-0.2	~ 0.0
Radiative	-2.7	-0.3	-1.4	~ 0.0	-1.0	~ 0.0	-6.4	-2.6
Electron collisional	~ 0.0	~ 0.0	~ 0.0	~ 0.0	~ 0.0	~ 0.0	~ 0.0	~ 0.0
Electron Landau	-0.1	-0.1	~ 0.0	~ 0.0	~ 0.0	~ 0.0	~ 0.0	~ 0.0
Ion Landau	~ 0.0	~ 0.0	-0.1	~ 0.0	-0.1	~ 0.0	~ 0.0	-0.1
He3 minority	-0.2	-0.1	-0.2	-0.1	-0.2	-0.1	-0.2	-0.4
Alphas	$+0.1$	~ 0.0	$+0.6$	$+0.3$	$+0.8$	$+0.3$	$+0.2$	$+0.7$
Total w/o fast ions	-2.9	-0.4	-1.6	-0.1	-1.1	-0.1	-6.6	-2.8
Total w/ fast ions	-3.0	-0.5	-1.1	$+0.2$	-0.5	$+0.1$	-6.6	-2.4

ORBIT calculates wave-particle interactions (n = 10 TAE + alphas) over *all* of phase-space



ORBIT calculates wave-particle interactions (n = 10 TAE + He3) over *all* of phase-space